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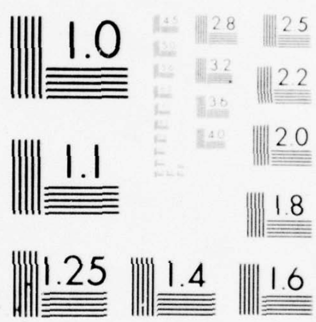

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Lethal Effects of Suspended Sediments on Estuarine Fish

by

J.M. O'Connor, D.A. Neumann, and J.A. Sherk, Jr.

TECHNICAL PAPER NO. 76-20
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A 3-year laboratory study identified certain estuarine fish sensitive to the effects of particle size and concentration of (a) suspended mineral solids similar in size to sediments likely to be found in estuarine systems in concentrations typically found during flooding, dredging, and disposal of dredged material, and (b) natural sediments in identical experiments. Significant mortality of estuarine fish was demonstrated at these suspended mineral solid concentrations. Estuarine fish were classified, using static

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bioassays as: Tolerant (24-hour $LC_{10} \geq 10$ grams per liter), sensitive (10 grams per liter > 24-hour $LC_{10} > 1.0$ gram per liter), or highly sensitive (24-hour $LC_{10} \leq 1.0$ gram per liter) to fuller's earth suspensions.

Generally, bottom-dwelling fish species were most tolerant to suspended solids; filter feeders were most sensitive. Early life stages were more sensitive to suspended solids than adults; filter feeders were most sensitive. Bioassays with natural sediments indicated that suspensions of natural muds affected fish in the same way as fuller's earth, but higher concentrations of natural material were required to produce the same level of response.

The effect of finely divided solids on fish was dependent on concentration, particle-size distribution, and angularity of the suspended particles. The cause of death was the same in all experiments--anoxia.

This study provides base-line information for preproject decision-making based upon the anticipated concentration of suspended sediments at the project site and the effect of various lengths of exposure on estuarine fish of different life-history stages and habitat preference.

PREFACE

This report is published to provide coastal engineers with information on the lethal effects of suspended sediments on estuarine organisms. The work reported is a part of a continuing program of research on the ecological effects of coastal engineering activities. The report presents the results of part of a 3-year laboratory study on the subject. The work was carried out under a contract originating in the Office, Chief of Engineers, which was monitored under the coastal ecology research program of the U.S. Army Coastal Engineering Research Center (CERC).

The original contract report (CERC Contract No. DACW72-71-C-0003) was prepared by Dr. J.M. O'Connor, Mr. D.A. Neumann, and Dr. J.A. Sherk, Jr., while on the staff of the Natural Resources Institute, University of Maryland, College Park, Maryland.

Mr. A.K. Hurme, CERC, technically reviewed, condensed, and revised that part of the original report pertaining to the lethal effects of suspended solids on estuarine fish. Mr. Robert M. Yancey, Chief, Ecology Branch, was CERC contract monitor for the report, under the general supervision of Mr. R.P. Savage, Chief, Research Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.
To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

LETHAL EFFECTS OF SUSPENDED SEDIMENTS ON ESTUARINE FISH

by

J.M. O'Connor, D.A. Neumann, and *J.A. Sherk, Jr.*

I. INTRODUCTION

Previous reports on the lethal effects of suspended particulate matter on estuarine fish have dealt with fine particles of commerical preparations such as kaolinite or fuller's earth (Rogers, 1969; Sherk and O'Connor, 1971; Sherk, O'Connor, and Neumann, 1972; Sherk, O'Connor, and Neumann, 1976), or with suspensions of fine particles of varied and undetermined compositions such as incinerator fly ash (Rogers, 1969). Studies of the effects of natural suspended solids on fish usually were concerned with growth, yield, or abundance-diversity determinations in natural communities (Ellis, 1936, 1937; Stickney, 1972; European Inland Fisheries Advisory Commission, 1964).

The primary objective of this study was to differentiate the effects of suspended natural sediments from the effects of suspended mineral particles on estuarine fish. The results of bioassay tests conducted with five species of estuarine fish exposed to suspensions of fuller's earth and resuspended natural sediments are presented (see also Sherk and O'Connor, 1971; Sherk, O'Connor, and Neumann, 1972; Sherk, O'Connor, and Neumann, 1976).

The fish species tested in suspensions of mineral solids and natural sediments were: White perch (*Morone americana*), spot (*Leiostomus xanthurus*), menhaden (*Brevoortia tyrannus*), striped killifish (*Fundulus majalis*), and mummichog (*F. heteroclitus*). Represented within this group are the common littoral or shallow-water estuarine fish (striped killifish and mummichog), filter-feeding fish which use the estuary primarily as a nursery ground (menhaden), and two pelagic (open water) fish (white perch and spot). Fish in this range of diverse habitats and feeding habits were chosen to provide (a) an estimate of the range of tolerance among different estuarine fish exposed to highly turbid waters, and (b) the differing effects of fine commercial, industrial, or natural particles on typical estuarine fish.

II. MATERIALS AND METHODS

1. General.

The lethal effects of suspended solids on fish were determined by static bioassay test procedures. Test groups were simultaneously exposed to four different concentrations of suspended solids and one group was a control (no added suspended solids). Particle concentration varied, depending upon the species tested and the duration of the test (12, 18, 20, 24, and 48 hours).

Sediment was maintained in suspension during the test period by continuous agitation with a submersible pump and aeration by injection of compressed air. The control tank received the same pumping and aeration treatment.

Fuller's earth (Fisher F-90, technical grade), kaolinite (Hydrite-10, Georgia Kaolin Company, Elizabeth, New Jersey), and resuspended bottom sediments from the upper Patuxent River estuary were used in the bioassay experiments. Concentrations in the experimental tanks were determined by weight. Replicate 5-milliliter samples were drawn from test and control tanks and dried. The difference between the weight of the dried control sample and the dried test tank sample represented the added sediment load in grams per liter ($g\ l^{-1}$).

Fish were exposed to suspended solids in 27-liter polyethylene tanks. Temperatures were maintained within ±1.5° Celsius by immersing the test tanks in a circulating water bath. Tanks were monitored for fish mortality, temperature, pH, and dissolved oxygen.

Lethal concentrations (LC) of suspended solids causing 10-, 50-, and 90-percent mortality of test fish were determined by normit analysis (personal communication, McErlean, Environmental Protection Agency, 1969), a modification of probit analysis (Berkson, 1953).

2. Bioassays Using Mineral Solids.

Tests using commercial preparations of the mineral solids, kaolinite and fuller's earth, were conducted using 14 fish species from two locations (Table 1). Six species were from Delaware Bay (bay anchovy, *Anchoa mitchilli*; Atlantic silverside, *Menidia menidia*; croaker, *Micropogon undulatus*; weakfish, *Cynoscion regalis*; bluefish, *Pomatomus saltatrix*; and cusk eel, *Rissola marginata*). Eight species were from the Patuxent River estuary, Maryland (spot; toadfish, *Opsanus tau*; mummichog; hogchoker, *Trinectes maculatus*; menhaden; white perch; striped bass, *Morone saxatilis*; and striped killifish). Bioassay tests for the Delaware Bay fish were conducted at the University of Delaware Bayside Laboratory, Lewes, Delaware; tests for the Patuxent River estuary fish were conducted at the University of Maryland Hallowing Point Field Station, Prince Frederick, Maryland.

Fish were collected by otter trawl or haul seine and transported in water to holding facilities. Bayside Laboratory holding facilities consisted of 140-liter polyethylene tanks immersed in temperature-controlled water baths. Water quality at Bayside was maintained by a combination of aeration and filtration in a closed-system recirculating unit. Hallowing Point holding facilities consisted of 250-liter polyethylene tanks immersed in temperature-controlled water baths. An inline protein skimmer device was used to maintain water quality in the closed system.

All fish were starved for 2 to 5 days before testing. Hydrite-10 and fuller's earth were analyzed for particle size, organic content, and

Table 1. Test species.

Species			
Scientific name	Common name[1]	Capture location[2]	Capture method[3]
Brevoortia tyrannus	Menhaden	Del.	H.S.
Anchoa mitchilli	Bay anchovy	Del.	H.S.
Fundulus majalis	Striped killifish	P.R.	H.S.
F. heteroclitus	Mummichog	P.R.	H.S.
Rissola marginata	Cusk eel	Del.	H.S.
Menidia menidia	Atlantic silverside	Del.	H.S.
Morone saxatilis	Striped bass	P.R.	O.T.
Morone americana	White perch	P.R.	O.T.
Leiostomus xanthurus	Spot	P.R.	O.T.
Micropogon undulatus	Croaker	P.R.	O.T.
Cynoscion regalis	Weakfish	Del.	H.S.
Trinectes maculatus	Hogchoker	P.R.	O.T.
Pomatomus saltatrix	Bluefish	Del.	H.S.
Opsanus tau	Oyster toadfish	P.R.	O.T.

[1]From American Fisheries Society Special Publication No. 6.
[2]Del., University of Delaware Bayside Laboratory, Lewes, Delaware.
P.R., Patuxent River estuary, Maryland.
[3]H.S., 15.24-meter beach seine.
O.T., 6.096-meter otter trawl pulled at 3 knots for 3 to 5 minutes.

acid-extractable cations (see App.). Since water temperature and salinity at the Bayside Laboratory fluctuated with tides, the fish were tested at a median temperature of 22° ± 2° Celsius and at the same salinity as that at the time and place of capture. Salinity range during testing was 18 to 30 parts per thousand ($^{o}/oo$).

The fish at Hallowing Point were captured in water of 4 to 6 $^{o}/oo$ salinity over a temperature range of 15° to 27° Celsius. Tests were conducted at approximately 5.5 $^{o}/oo$ salinity and at 25° ± 2° Celsius.

3. Bioassays Using Resuspended Natural Sediments.

All natural sediment bioassay tests were made at Hallowing Point. Sediment was obtained in 6.1 meters of water near Long Point in the Patuxent River estuary. Several samples were obtained at one time and were mixed before use. Although the same batch of sediment was not used in all tests, results using different sediment batches were repeatable.

Natural sediments were kept in polyethylene containers and were covered with saline water (4 to 6 $^{o}/oo$).

Natural sediments were added to test tanks as a mud-water slurry. Test tanks were partially filled with the slurry, and the concentration of solids was determined. The slurry was then diluted with filtered river water to obtain the desired test concentration.

III. RESULTS

1. Bioassays Using Mineral Solids.

Eleven of the 14 species used in this study were exposed to suspensions of kaolinite (Hydrite-10). All fish exposed to kaolinite survived 24-hour exposure in concentrations as high as 140 g l^{-1}. Several species (white perch, spot, toadfish, mummichog, hogchoker, and menhaden) were exposed to 140 g l^{-1} kaolinite for 48 hours with the same result; no deaths were directly attributable to the mineral. Usually, the fish became highly active for a short time when placed in kaolinite suspensions. Activity returned to normal after 0.5 to 2 hours. Three species (bluefish, cusk eel, and bay anchovy) were not exposed to kaolinite because too few individuals were collected.

Survival of the 14 species was assessed in suspensions of fuller's earth. Three species (toadfish, cusk eel, and hogchoker) showed no mortality attributable to the effects of fuller's earth after 24-hour exposure to concentrations of 96 to 140 g l^{-1}.

The response of 5 of the 11 species killed in the fuller's earth suspension (striped bass, croaker, weakfish, bluefish, and menhaden) was not consistent enough to calculate accurate LC values. The tolerance of these fish, as the lowest concentration at which 100-percent mortality occurred, is presented in Table 2.

Exposure of the remaining six species (Atlantic silverside, striped killifish, white perch, bay anchovy, spot, and mummichog) to fuller's earth resulted in consistent concentration mortality responses. From these responses, calculations of lethal concentrations for 10-, 50-, and 90-percent mortality in 24-hour bioassays were made. Consistent concentration mortality responses of white perch were observed for 12-, 18-, and 24-hour exposures. Spot showed consistent responses for the 12-, 20-, and 48-hour exposures.

The six species varied widely in sensitivity to suspensions of fuller's earth, as indicated by 24-hour lethal concentration (Table 3) and concentration-dependent response curves (Fig. 1). The LC_{50} response range was 36.60 g l^{-1} and varied from 2.40 g l^{-1} (Atlantic silverside) to 39.00 g l^{-1} (mummichog). LC_{90} values for 24-hour assays had a range of 56.57 g l^{-1}, from 9.60 g l^{-1} (bay anchovy) to 62.17 g l^{-1} (mummichog). The total range of LC_{10} values was 23.90 g l^{-1}, from 0.57 g l^{-1} (Atlantic silverside) to 24.47 g l^{-1} (mummichog).

The concentration range from LC_{10} to LC_{90} within each species varied widely. The species with the highest LC_{50} value (mummichog) showed a range of 37.70 g l^{-1} between LC_{10} and LC_{90} (Table 3). The species with the lowest LC_{50} value (Atlantic silverside) showed a range of 9.43 g l^{-1} between LC_{10} and LC_{90}. Species with intermediate 24-hour LC_{50} values (white perch and spot) showed ranges of 28.76 and 18.54 g l^{-1}, respectively,

Table 2. Lowest fuller's earth concentration causing 100-percent mortality in a 24-hour exposure for five estuarine fish.

Species	Age class	Individuals (No.)	Test conditions		
			Salinity (°/oo)	Temperature (°C)	Concentration g l^{-1} fuller's earth
Menhaden	0+	30	5.5	25 ± 2	1.2
Menhaden	1+	60	23.6	22 ± 2	0.8
Bluefish	1+	26	20.0	22 ± 2	0.8
Weakfish	0+	47	20.0	22 ± 2	6.8
Weakfish	0+	20	5.5	25 ± 2	8.2
Striped Bass	2+	31	5.5	25 ± 2	16.6
Croaker	1+	17	5.5	25 ± 2	11.4

Table 3. LC_{10}, LC_{50}, and LC_{90} values determined for 24-hour exposure of estuarine fish.

Species	r	r^2	Lethal concentration (g l^{-1} fuller's earth)					
			LC_{10}	log LC_{10}	LC_{50}	log LC_{50}	LC_{90}	log LC_{90}
White perch	0.938	0.880	3.05	0.484	9.85	0.993	31.81	1.503
Spot	1.000	1.000	13.08	1.117	20.34	1.308	31.62	1.500
Bay anchovy	0.760	0.578	2.31	0.364	4.71	0.673	9.60	0.982
Atlantic silverside	0.806	0.650	0.57	-0.244	2.40	0.380	10.00	1.000
Mummichog	0.952	0.906	24.47	1.389	39.00	1.591	62.17	1.794
Striped killifish	0.966	0.933	23.77	1.376	38.18	1.582	61.36	1.788

[1]Correlation coefficients (r) and coefficients of determination (r^2) derived from regression analyses are presented as statistical estimates of the decimal fraction of mortality accounted for by concentration effects.

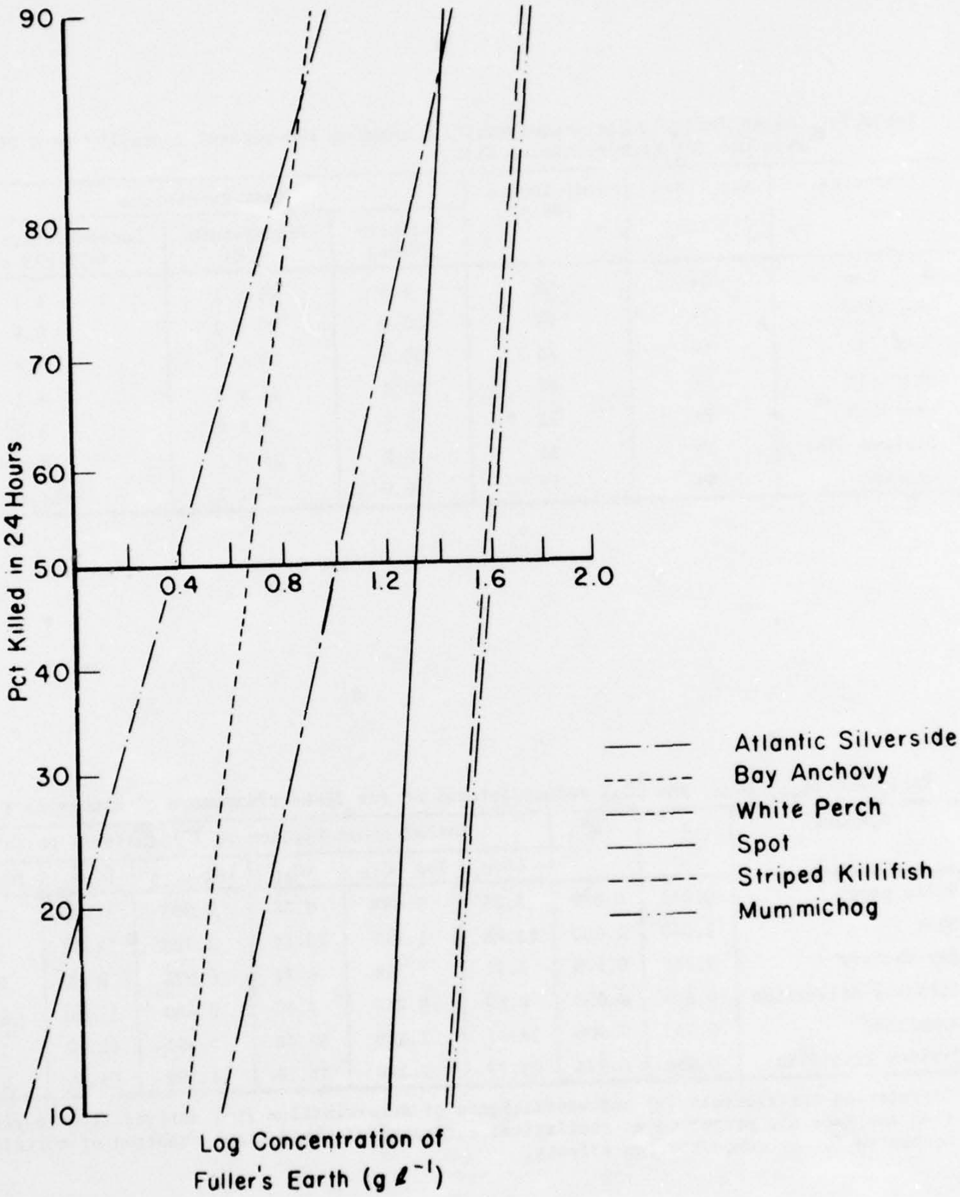

Figure 1. Twenty-four-hour concentration-mortality curves for six species of estuarine fish exposed to fuller's earth.

between LC_{10} and LC_{90}. The range of concentration between LC_{10} and LC_{90} did not necessarily reflect the sensitivity of the species as indicated by the 24-hour LC_{50} value. For example, the LC_{10} to LC_{90} range for white perch was 28.76 g l^{-1}; spot, with a 24-hour LC_{50} more than twice that of white perch (20.34 versus 9.85 g l^{-1}) had an LC_{10} to LC_{90} range of only 18.54 g l^{-1}. Similarly, bay anchovies (LC_{50} = 4.71 g l^{-1}) had an LC_{10} to LC_{90} range of 7.29 g l^{-1}; the more sensitive Atlantic silverside (LC_{50} = 2.40 g l^{-1}) had an LC_{10} to LC_{90} range of 9.43 g l^{-1}.

White perch and spot exposed to fuller's earth for varying times showed an overall reduction of LC_{10}, LC_{50}, and LC_{90}, with increasing duration of exposure (Table 4). These values were plotted logarithmically and are presented as toxicity curves (Figs. 2 and 3) (Sprague, 1969) and as concentration mortality curves (Figs. 4 and 5).

Table 4. LC_{10}, LC_{50}, and LC_{90} values for white perch and spot, with increasing duration of exposure to fuller's earth.

Duration of bioassay (h)	White perch			Spot		
	LC_{10}	LC_{50}	LC_{90}	LC_{10}	LC_{50}	LC_{90}
12	32.07	41.00	52.41	27.56	42.36	65.12
18	-----[1]	-----	-----	21.07	33.06	51.87
20	7.91	14.99	28.38	-----	-----	-----
24	3.05	9.85	31.81	13.08	20.34	31.62
48	0.67	2.96	13.06	1.13	1.90	3.17

[1]Not tested.

2. Bioassays Using Resuspended Natural Sediments.

Lethal concentrations of natural sediments during 24-hour exposures were determined for white perch, spot, menhaden, and striped killifish, and compared with the 24-hour LC values for fuller's earth (Table 5).

Table 5. Comparison of 24-hour LC values of fuller's earth and natural Patuxent River, Maryland, sediments.

LC g l^{-1}	Sediment	Species		
		White perch	Spot	Striped killifish
LC_{10}	Natural	9.97	68.75	97.1
	Fuller's earth	3.05	13.81	23.77
LC_{50}	Natural	19.80	88.00	128.2
	Fuller's earth	9.85	20.34	38.18
LC_{90}	Natural	39.40	112.63	169.3
	Fuller's earth	31.81	31.62	61.36

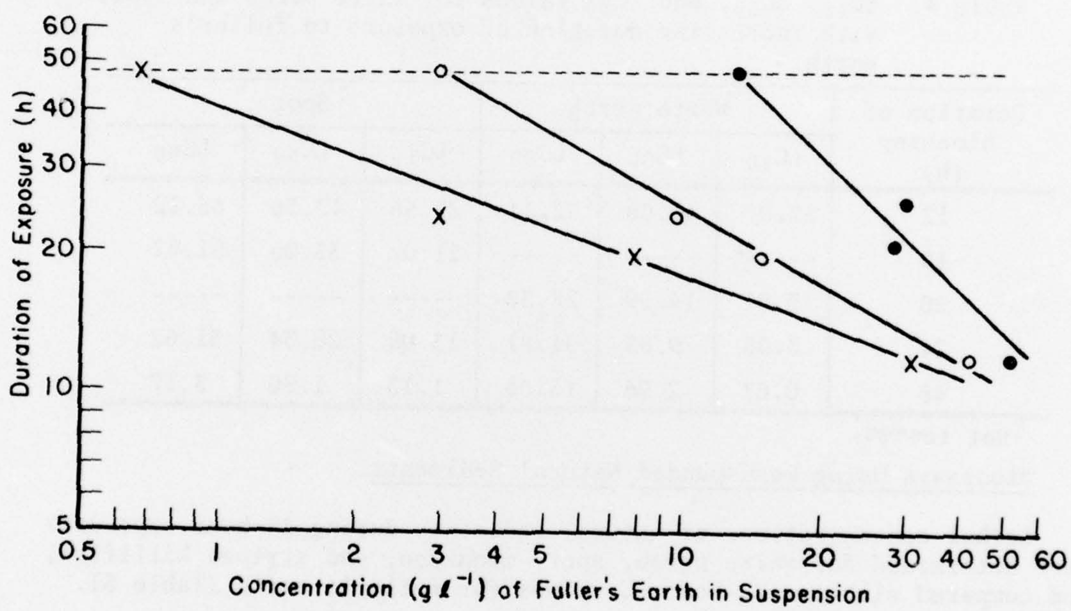

Figure 2. Effect of fuller's earth on white perch, LC_{90} (solid points), LC_{50} (open points), and LC_{10} (x). Dotted line indicates 48-hour exposure, the maximum duration of exposure.

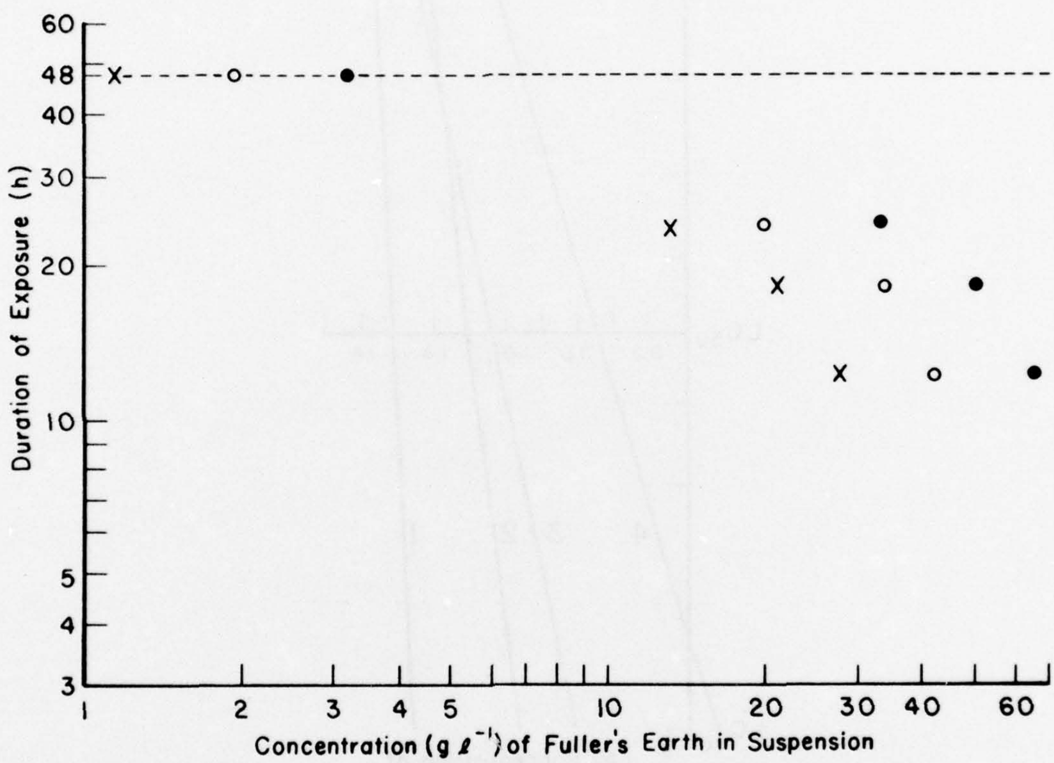

Figure 3. Effect of fuller's earth on spot, LC_{90} (solid points), LC_{50} (open points), and LC_{10} (x). Dotted line indicates 48-hour exposure, the maximum duration of exposure.

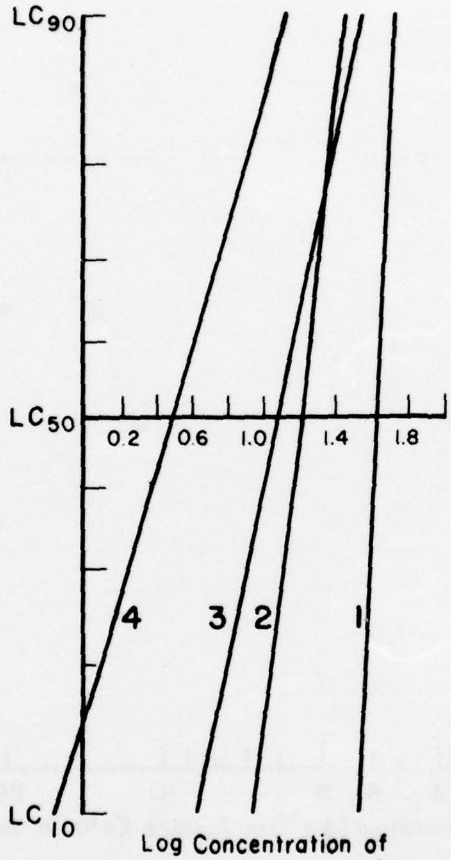

Figure 4. Concentration mortality curves for white perch exposed to suspensions of fuller's earth for 12 hours (1), 20 hours (2), 24 hours (3), and 48 hours (4).

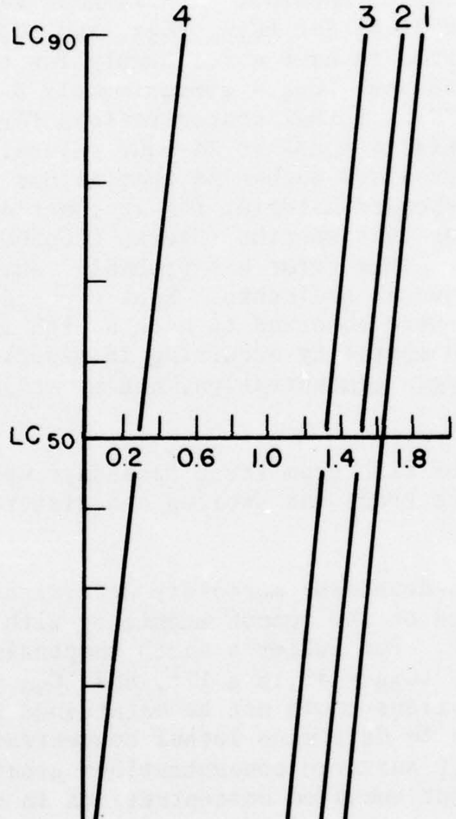

Figure 5. Concentration mortality curves for spot exposed to suspensions of fuller's earth for 12 hours (1), 18 hours (2), 24 hours (3), and 48 hours (4).

The LC_{50} value for white perch exposed to resuspended natural sediments was 19.80 g l^{-1}; the LC_{50} value for fuller's earth was 9.85 g l^{-1}. A similar range applied to LC_{90} and LC_{10} values in resuspended natural sediments when compared with fuller's earth, and varied between 39.40 versus 31.81 g l^{-1} (LC_{90}) and 9.97 versus 3.05 g l^{-1} (LC_{10}), respectively.

Spot exposed to natural sediments had a LC_{50} value of 88.00 g l^{-1}, and LC_{10} and LC_{90} values of 68.75 and 112.63 g l^{-1}, respectively, for a 24-hour exposure. These values contrast with 24-hour values of fuller's earth at 13.81, 20.34, and 31.62 for LC_{10}, LC_{50}, and LC_{90}, respectively. Spot were previously reported to have a relatively low tolerance to resuspended natural sediment (48-hour LC_{50} = approximately 3 g l^{-1}) (Sherk, O'Connor, and Neumann, 1972). Lethal concentrations for replicated 48-hour exposures were essentially equal to 24-hour values. This suggests that (a) spot have a compensatory mechanism that allows them to tolerate high levels of natural suspended material for at least 48 hours, and (b) the preliminary results for this species (Sherk, O'Connor, and Neumann, 1972, p.24) were in error. This error was probably caused by inadequate oxygenation of the experimental sediments. Spot exposed to these suspensions of natural material were observed to have a high initial oxygen demand. As a result, high mortality occurring in experimental tanks was probably caused by low oxygen concentration, not by sediment concentrations.

The alimentary canal of fish from these bioassays was packed with sediment. The entire digestive tract was swollen and distorted by ingested material.

Separate concentration-dependent mortality determinations (48 hours, 25° Celsius) were conducted on the common mummichog with both fuller's earth and natural sediment. For fuller's earth suspensions, 48-hour values were: LC_{10} = 35.86 g l^{-1}, LC_{50} = 45.16 g l^{-1}, and LC_{90} = 56.89 g l^{-1}. Natural sediment concentrations could not be maintained high enough to cause sufficient mortality to determine lethal concentrations. Sixty-two percent of adult mummichogs survived concentrations greater than 125 g l^{-1} for 24 hours and 100 percent survived concentrations in excess of 109 g l^{-1} for 72 hours.

Striped killifish exposed to resuspended natural sediments for 24 hours had LC_{10}, LC_{50}, and LC_{90} values of 97.1, 128.2, and 169.3 g l^{-1}, respectively.

IV. DISCUSSION

The effects of suspended natural and mineral sediments on estuarine fish are partially dependent on certain characteristics of the suspended materials. No species, including menhaden, died in suspensions of kaolinite clay (median particle size of 0.55 micrometer). Menhaden are highly sensitive to suspensions of solids other than kaolinite. However, suspensions of fuller's earth in concentrations exceeding 0.65 g l^{-1} were

lethal to most species. Physical comparison of the two mineral solids suggests that the differences in the lethal effects of these substances (Table 5) may be due in part to particle-size distribution (see App.).

Suspended solid particles of differing composition vary greatly in lethal effect on fish (European Inland Fisheries Advisory Commission, 1964; Rogers, 1969). Using a variety of solids (kaolinite, diatomaceous earth, natural glacial till, and incinerator fly ash), Rogers (1969) concluded that the lethal effect of a suspended solid is dependent on particle shape and angularity rather than on particle size. However, it is not known how particle angularity causes rapid (24 to 96 hours) mortality in test fish.

Common symptoms in dead and moribund test fish are extensive hemorrhaging of minute blood vessels over the entire body surface and packing of the gills with sediment. Microscopic examination of fresh gill preparations from recently dead fish showed no hemorrhaging associated with exposure to kaolinite or fuller's earth. Rogers' (1969) hypothesis could not be evaluated because particles of kaolinite and fuller's earth were flat and platelike, and the sand grains in the natural sediments were relatively smooth.

Respiration studies show some effects of suspended mineral solids on fish. Rogers (1969) noted increased survival among test fish when he bubbled air into his test chambers. This suggests that exposure to suspended solids leads to anoxia. The relationship between particle angularity and the lethal effect may result from angular particles having a greater affinity for the gill surface, thus causing anoxia by covering or abrading the respiratory epithelium.

Natural sediment suspensions were less harmful than mineral solid suspensions for every species tested (Table 5). The lethal effect of the natural mud probably was due to clogging of the gill interstices, as opposed to the coating effect of fuller's earth particles. Ellis (1937) described several ways in which particles could cause asphyxiation in fish; e.g., coating by fine particles and clogging by larger particles such as those found in natural mud.

Although Ellis' discussion did not include details of fish gill morphology, investigations by Muir (1969) and Cameron and Davis (1970) support the hypothesis that suspended particulate matter is lethal to fish at concentrations well in excess of those observed in nature. The lethal effect of finely divided solids on fish depends on several factors although the cause of death is the same--anoxia. Fine particles generally will not cause death unless the particles are angular. Larger particles trapped by the primary and secondary lamellae of the gill block the minute circulation channels between the secondary lamellae. This leads to "dead space" at the primary site of gas exchange; limited oxygen diffusion occurs in these dead spaces. A coating of clay particles over the entire gill surface would be less likely to permit gas exchange.

Fish may be able to tolerate greater concentrations of natural sediments than mineral solids because: (a) The abrasive mineral particles are diluted by organic material in the natural sediment and therefore are not as damaging, or (b) the larger natural particles allow water to flow through the larger interstices and reach the gill surface.

In freshwater systems, concentrations of 2 to 6 g l^{-1} of silt may persist for 15 to 20 days in flood-stage rivers (European Inland Fisheries Advisory Commission, 1964). Similarly, freshwater streams polluted with china-clay mining waste may carry burdens of 1 to 6 g l^{-1}, continuously (Herbert and Merkins, 1961). Saline waters carry lower concentrations of suspended particles because of flocculation, dilution, and the "salting-out" phenomenon. However, Masch and Espey (1967), in a study of shell-dredging operations in Galveston Bay, Texas, recorded suspended solid concentrations of 4.15 g l^{-1} in the immediate vicinity of a dredge discharge. Concentrations were 0.3 g l^{-1} suspended solids 838.2 meters from the discharge. Suspended solid concentrations may reach 1.2 g l^{-1} during flood conditions, such as Hurricane Agnes in 1972, in the upper Patuxent River, Maryland. Values recorded during the summer of 1972 were generally between 0.08 and 0.14 g l^{-1}, depending on local weather conditions and tidal scouring. Suspended solid concentrations capable of causing significant mortality in certain estuarine fish species at the 10- and 50-percent levels can be maintained in estuarine systems near dredging operations or during times of excessively high runoff.

The relationship between suspended solid concentrations and their effect on mortality with increasing exposure time are shown in Table 4. Arithmetic plots (Figs. 6 and 7) of the LC_{10} and LC_{50} data from Table 4 allow an estimation of the severity of the impact of a given concentration of fuller's earth upon white perch and spot. For white perch, the concentration of fuller's earth needed to cause 90-percent mortality for a 48-hour exposure (not shown) was 25 percent, by weight, of the 12-hour LC_{90} value. However, the LC_{10} value for white perch exposed to fuller's earth for 48 hours was only 2.2 percent of the 12-hour LC_{10} value. Thus, very low concentrations of suspended solids caused low, yet important levels of mortality during long exposure periods.

For white perch (Fig. 6), the LC_{10} duration of exposure had its effect primarily on the lower levels of mortality. Thus, using LC_{10} data (Fig. 6), it was found that the visual approximation afforded an excellent estimate of inflection between 20 and 24 hours at approximately 4 g l^{-1} fuller's earth.

Mortalities beyond the 48-hour LC_{10} approached zero. Extrapolated LC_{10} values for 72- and 96-hour exposures were 0.06 and 0.0045 g l^{-1}, respectively, or well within the range of suspended material carried by "undisturbed" natural systems.

Fish exposed to concentrations of suspended solids normally found in natural waters are not adversely affected by concentrations below a certain threshold value. The concentration of 0.0045 g l^{-1} is well below

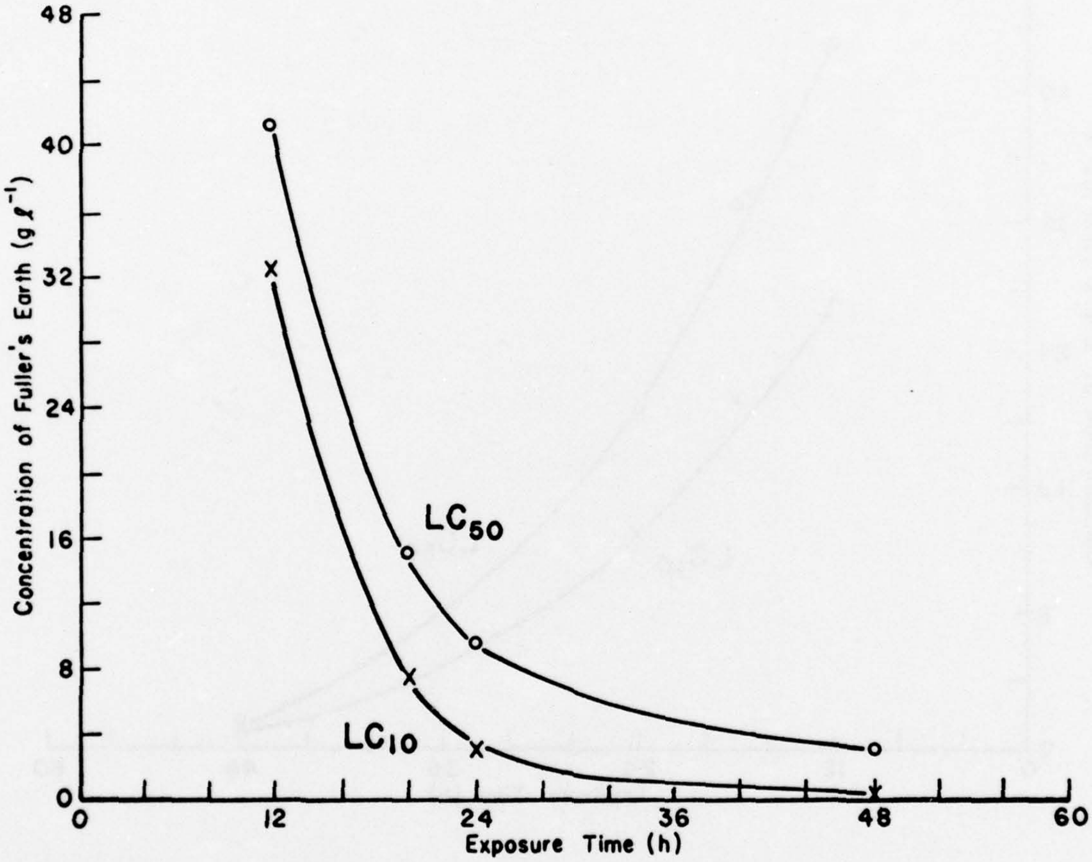

Figure 6. LC_{10} and LC_{50} values for white perch at 12-, 20-, 24-, and 48-hour exposures to suspensions of fuller's earth.

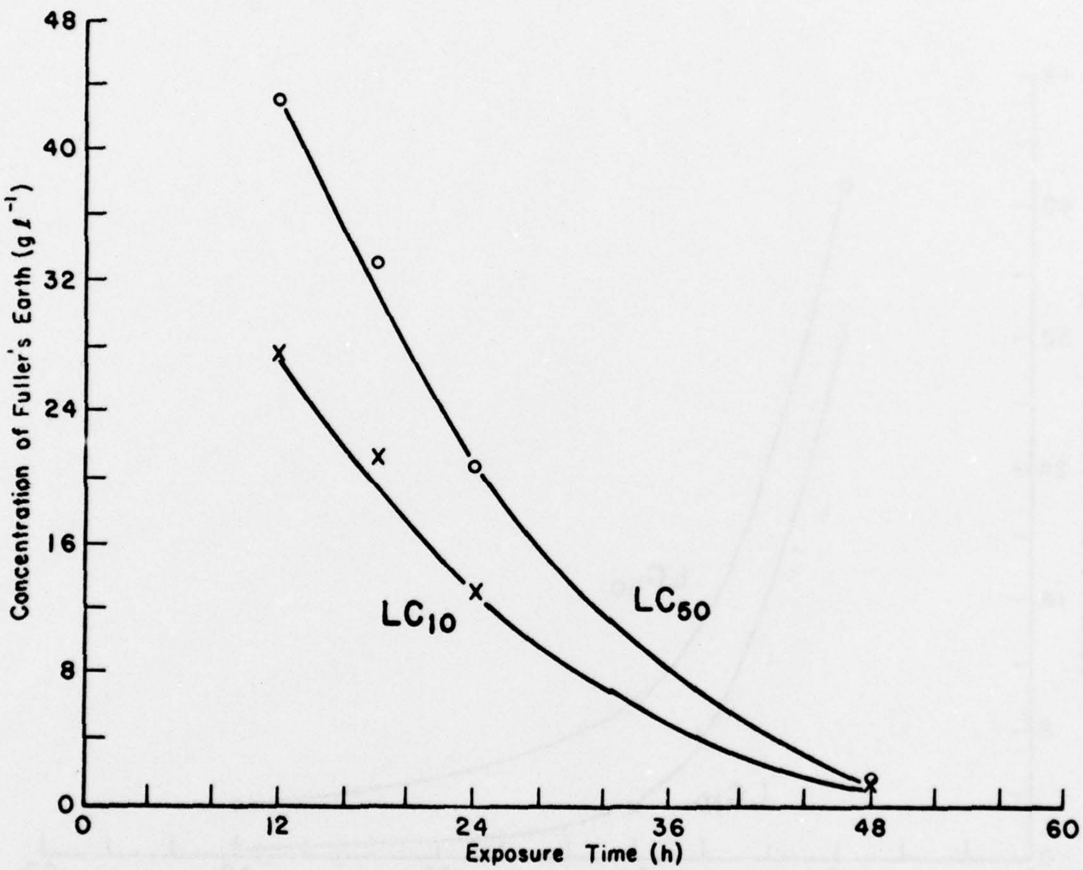

Figure 7. LC_{10} and LC_{50} values for spot at 12-, 18-, 24-, and 48-hour exposures to suspensions of fuller's earth.

that threshold. The concentration threshold for a given species may be determined by the ability of the fish to cleanse the gills by the coughing reflex, or by continuous secretion and sloughing of a protective mucus sheet.

The LC_{10} and LC_{50} curves (Fig. 7) for spot in suspensions of fuller's earth do not show a marked inflection point. The extrapolated 72- and 96-hour LC_{10} values for spot (0.135 and 0.017 g l^{-1}, respectively) would be within the range of concentrations found in natural waters.

White perch were exposed to suspended solids at 0.65 g l^{-1} for as long as 5 days (O'Connor, Neumann, and Sherk, in preparation, 1976). From an extension of the LC_{50} and LC_{10} curves relating exposure duration to concentration, concentrations of 0.65 g l^{-1} would be expected to cause 10-percent mortality in less than 5 days. A threshold concentration between 0.67 and 0.65 g l^{-1} appears to exist. Higher concentrations may cause death, at least at the 10-percent level, during exposure of 48 hours; lower concentrations are unlikely to cause death. However, fish exposed to 0.65 g l^{-1} for 5 days showed sublethal physiological changes in blood characteristics and damage to gill tissues (O'Connor, Neumann, and Sherk, in preparation, 1976).

V. CLASSIFICATIONS

Fish species used in these experiments may be placed in the following three groups according to their toleration of suspended solid concentrations. Classification is subjective and based on LC_{10} values of fuller's earth, because 10-percent mortality in addition to natural mortality rates is a more realistic maximum than a 50-percent mortality limit (Ricker, 1954).

(a) Class I: Suspension-Tolerant Species. The concentration of fuller's earth required to attain the 24-hour LC_{10} value is equal to or in excess of 10 g l^{-1}. Tolerant species were the mummichog, striped killifish, and spot. Toadfish, hogchoker, and cusk eel were tested for suspension tolerance, but concentration-dependent mortality curves were not determined. The tolerant species commonly inhabit the mud-water interface where suspended solid concentrations are high (Masch and Epsey, 1969); e.g., the killifish, hogchoker, and cusk eel frequently burrow into the bottom and remain covered for extended periods of time (Hildebrand and Schroeder, 1928). The toadfish is a relatively inactive bottom dweller (Hildebrand and Schroeder, 1928).

(b) Class II: Suspension-Sensitive Species. LC_{10} values for 24-hour exposure to fuller's earth were between 1 and 10 g l^{-1}. The sensitive species (white perch, bay anchovy, and juvenile menhaden) were tested at Hallowing Point (Sherk, O'Connor, and Neumann, 1973); their habitat preference with tolerance to fuller's earth was not correlated. Although specific LC_{10} values could not be determined, three important commercial species (the striped bass, croaker, and weakfish) were in this general class.

(c) Class III: Highly Sensitive Species. Twenty-four-hour LC_{10} values were less than or equal to 1 g l^{-1} of fuller's earth. Highly sensitive species were Atlantic silverside (24-hour LC_{10} value 0.57 g l^{-1}), juvenile bluefish, juvenile menhaden, and young-of-the-year white perch (Sherk and O'Connor, 1971). Juvenile bluefish and juvenile menhaden tested at the Bayside Laboratory failed to survive in concentrations of 0.8 g l^{-1} for more than 18 hours. Young-of-the-year white perch suffered 100-percent mortality in 0.75 g l^{-1} fuller's earth in 20 hours.

The lethal effects of suspended solids on fish species change at different stages in the life history. Juvenile white perch are more likely to be killed by low concentrations of suspended solids than are adults. The basis for such age specific differences in tolerance is unknown. When fish are exposed to lethal concentrations of fuller's earth, the gill filaments and the secondary lamellae act as a sieve to trap particles which clog the gill, resulting in asphyxiation (Ellis, 1937). The physical dimensions of the gill increase with the increasing size of the fish (Muir, 1969). As the fish grows and the gill dimensions increase, the openings in the gill filter also increase. Thus, large fish may trap fewer particles, thereby decreasing the lethal effect of a given concentration of suspended solids.

Another factor that may explain the link between fish size and tolerance is that small fish have a higher metabolic rate than large fish (O'Connor, Neumann, and Sherk, in preparation, 1976). Small fish demand more oxygen per unit body weight than large fish and therefore are less tolerant to gill clogging. The combined effects of a higher metabolic rate and a finer, more efficient filter render juveniles more sensitive to solids than adults.

VI. SUMMARY AND CONCLUSIONS

Static bioassays using fuller's earth suspensions and natural sediment suspensions produced significant mortalities in five common estuarine fishes--white perch, spot, Atlantic silversides, mummichog, and striped killifish. Concentrations typically found in estuarine systems during natural events such as storms and flooding, as well as during dredging and dredged material disposal, are within the range of the lethal concentrations of fuller's earth determined experimentally. Therefore, the possible adverse impact on fish populations of activities producing suspended sediment should be considered. Most fish are capable of avoiding or temporarily leaving a hostile environment.

The particulate mineral solids were similar in size distribution to natural sediments likely to be found in estuarine systems. Suspensions of natural sediments affect fish in the same way as fuller's earth but higher concentrations of the natural sediments are required to produce the same level of mortality. Death is caused by anoxia resulting from blockage of small passages in the gills or abrasion of the gill tissue. The effect of finely divided solids is dependent upon concentration,

particle-size distribution, and angularity. In addition, other factors, which were uncontrolled and not covered in this study, must be considered when dealing with natural sediments. These factors may include sorbed toxic metals, high biochemical oxygen demand, and nutrient content.

Concentration-response curves were established to predict mortality for selected estuarine fish exposed to suspended particles. Lethal concentrations of fuller's earth causing a 10-percent mortality in 24 hours of exposure (24-hour LC_{10}) ranged from 0.57 g l^{-1} for Atlantic silversides to 24.5 g l^{-1} for mummichogs. Fish exposed to fuller's earth were classified as tolerant (24-hour $LC_{10} \geq 10$ g l^{-1}), sensitive (24-hour $LC_{10} > 10 > 1.0$ g l^{-1}), or highly sensitive (24-hour $LC_{10} \leq 1.0$ g l^{-1}). The use of lethal concentration levels causing 10- or 50-percent mortality over a defined period of exposure (hours or days) to establish suspended solid criteria is customary and useful. However, this procedure ignores the biologically significant sublethal effects of suspended solids on estuarine organisms.

The tolerances of various estuarine fish can be generalized. The most lethal effects of suspended mineral solids were found in: (a) Fish in the lower trophic levels (anchovies, Atlantic silversides, and juvenile white perch), (b) juvenile fish, and (c) species with high oxygen requirements. Species with very low oxygen requirements only succumb to very heavy concentrations of suspended solids, or not at all. These degrees of tolerance tend to be correlated with species habitat preferences. Pelagic (open water) and littoral (shoal water) fish were all affected by suspensions of solids, but to widely varying degrees. Benthic (bottom-dwelling) species that live in or at the mud-water interface were the least affected.

Dredging and dredged material deposition (particularly open-water disposal) should be timed and located, if possible, to: (a) Avoid spawning grounds and times, and also areas used by juvenile fish; (b) avoid areas used by lower trophic level fish, particularly filter-feeders; and (c) avoid areas used by pelagic and littoral fish with high oxygen requirements.

Adequate knowledge of local conditions at dredging and dredged material disposal sites is essential for preproject decisionmaking; i.e., species present (seasonal and resident), habitat preference, life history stages, sediment types, sediment chemistry, sediment concentrations, and probable duration of exposure.

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APPENDIX

ANAYLSES OF SEDIMENTS

I. INTRODUCTION

Experimental work during 1971 and 1972 utilized artificial, commercially available mineral solids to provide base-line data for biological effects of (a) concentrations of solids, (b) different particle-size distributions, and (c) different mineral types of solids.

Work during 1973 concentrated heavily on the biological effects of naturally occurring sedimentary material which was collected by anchor dredge at Long Point (38°29'30" N., 76°39'45" W.) in the Patuxent River, Maryland, and stored in large polyethylene tanks before use in the experiments. The sediment surface was covered with a layer of water (salinity range 4 to 6 parts per thousand) to maintain natural ionic equilibria between the sediment and water, as would naturally occur in the Patuxent River. A microoxidized sediment layer developed at the sediment-water interface in tanks after a few days of storage.

This appendix contains the results of analyses which were performed on both the commercially available mineral solids and the naturally occurring sediments. Sediment characteristics measured were organic matter content (weight loss on ignition), inorganically bound heavy metals (atomic absorption analysis), and particle-size distributions (settling diameter analysis).

The particle-size distributions were determined in distilled water, and may represent the basic or fundamental unit particles which can form aggregates with other units and be strongly bound by molecular and atomic forces. These composite units are stable under dispersion methods. Also, the basic particles may form agglomerates in saline water. These composites are relatively weakly bonded by electrostatic forces, surface tension, and "sticky" organic matter.

II. MATERIALS AND METHODS

1. Size Distribution.

Fuller's earth (Fisher F-90) and kaolinite (Hydrite-10, Georgia Kaolin Company) were the artificial sediments (mineral solids) used in this study. Particle-size distributions of these materials were determined by the sedimentation method (American Society of Testing and Materials, 1968) for paper-coating clays. In addition, a finer particle-size distribution of silica (SiO_2) was generated from a commercially available Fisher No. S-135 by allowing these solids to settle for 25 minutes through a specified distance in a column of distilled water at 20° Celsius. The solids finer by weight than 15 micrometers were calculated to be remaining in suspension in this column of water from tables presented by Trask (1968) and from Casagrande's nomographic solution of Stokes' law given in American Society

of Testing and Materials (1968). The suspended particles were decanted, ovendried for 24 hours at 100° Celsius, ground fine with a porcelain mortar and pestle, and analyzed for size distribution by the American Society of Testing and Materials (1968) method performed for the other mineral solids. This particular size distribution of SiO_2 particles is referred to in this report as less than 15 micrometers SiO_2.

The natural sediments collected from the Patuxent River were analyzed by a slightly modified procedure from the above method. Preliminary work showed that this material was approximately 75- to 80-percent salt and water by weight. Appropriate triplicate volumes of this natural material were removed from the holding tanks. These volumes were calculated to contain between 5 and 10 grams of dry solids (inorganic). Also, these volumes were corrected upward for the amount (weight) of organic matter present. These quantities of solids were placed into large Pyrex beakers (1-liter capacity) and an appropriate amount of 30 percent hydrogen peroxide (H_2O_2) was added to each beaker. The amount (volume) of H_2O_2 (30 percent) needed to oxidize the organic matter present in the sediment was found to be a volume which would produce a final concentration of H_2O_2 in the sediment volume of approximately 5 percent. The oxidation reaction was quite violent initially. The reaction was allowed to proceed overnight in a hood with air bubbling slowly through the sediment-H_2O_2 mixture to remove the excess H_2O_2.

When gas evolution had ceased the following day, 750 milliliters of deionized glass-distilled water were added to each beaker. The sediment was resuspended by stirring with a glass rod and allowed to settle. The supernatant was carefully decanted and another 750 milliliters of deionized glass-distilled water rinse were added to each beaker.

A 0.2-milliliter sample of supernatant water was then taken from each beaker and the dissolved ion concentration of each solution was determined with the freezing-point depression osmometer normally used in our hematological analyses. Salt concentration was read from a standard curve relating freezing-point depression and osmolal concentration to sodium chloride (NaCl) concentration in milligram kilogram^{-1} water. If the salt concentration was greater than 300 milligrams NaCl kilogram^{-1} water, the suspension was allowed to settle, the clear supernatant was decanted, and an additional rinse of 750-milliliter deionized distilled water was added to each beaker. The sediment was resuspended and allowed to settle. The clear supernatant was decanted and the beaker containing the washed sediment made up to 500 milliliters with fresh, deionized glass-distilled water was placed into an ultrasonic bath (45 kilohertz) for 30 minutes. Then, the suspension was placed into a glass cylinder, made up to volume with deionized distilled water, and the analysis followed as described in American Society of Testing and Materials (1968), except that the dispersing agent, sodium pyrophosphate ($Na_4P_2O_7$), was not added.

Values are reported as percent by weight remaining in suspension (percent finer than) plotting against equivalent spherical diameters according to Stokes' law.

2. Organic Matter Content.

Samples of the natural sediment collected from the Patuxent River at Long Point were ovendried for 24 hours at 100° Celsius, ground fine with a porcelain mortar and pestle, and ashed for 3 hours at 500° Celsius. Organic matter values are reported as percent loss of dry weight on ignition. There was no appreciable loss of inorganic carbonate during the ashing procedure as evidenced by nonsignificant weight losses of calcium carbonate ($CaCO_3$) samples which were ashed along with the ovendried natural sediments.

3. Heavy Metals.

Amounts of extractable cations in the mineral solids and the natural sediment samples were determined with mild acid extraction and atomic absorption analysis at the Seafood Processing Laboratory, Crisfield, Maryland. Routine procedures for inorganically bound cations, as described by Perkin-Elmer Corporation (1971) and Soil Testing and Plant Analysis Laboratory (1970), were conducted for zinc, copper, iron, manganese, lead, cobalt, nickel, chromium, and cadmium. Mercury values reported are for total mercury from sediments digested for 1 minute in boiling aqua regia (Dow Method, CAS-AM-70.13, revised 22 June 1970, Chlorine Institute, Madison Avenue, New York, New York). Metal values are reported as milligram kilograms^{-1} dry weight of solids.

III. RESULTS AND DISCUSSION

1. Size Distributions.

Particle-size distributions of the extremely fine mineral solids and natural sediment used in this project are presented in Figure A-1 and Table A-1. Useful descriptions of these materials ranked coarsest to finest by median size are as follows: Patuxent River silt (composite less organic matter fraction, 11.5 percent of dry weight), median size = <0.8 micrometer, <2 micrometers = 72 percent; fuller's earth, montmorillonite and attapulgite (Fisher No. F-90), median size = <0.5 micrometer, <2 micrometers = 82 percent; and kaolinite, Hydrite-10, (Georgia Kaolin Company), median size = <0.5 micrometer, <2 micrometers = 92 percent.

These data have been presented in such a way that graphic solutions (Folk, 1968) and mathematical calculations (Trask, 1968) can be used to determine the second, third, and fourth moments of these distributions.

Additional size-distribution analyses for the natural sediments (by date of collection) are presented in Figure A-2 and Table A-2. Median sizes ranged from a high of approximately 1.1 to a low of <0.5 micrometer (August collection). Fraction by weight finer than 2 micrometers ranged from a high of approximately 82 percent to a low of 65 percent (August collection). These particle-size distributions of solids used in our work (Tables A-1 and A-2, Figs. A-1 and A-2) are comparable with those reported by May (1973) in the mudflow from a shell dredge (Table A-3).

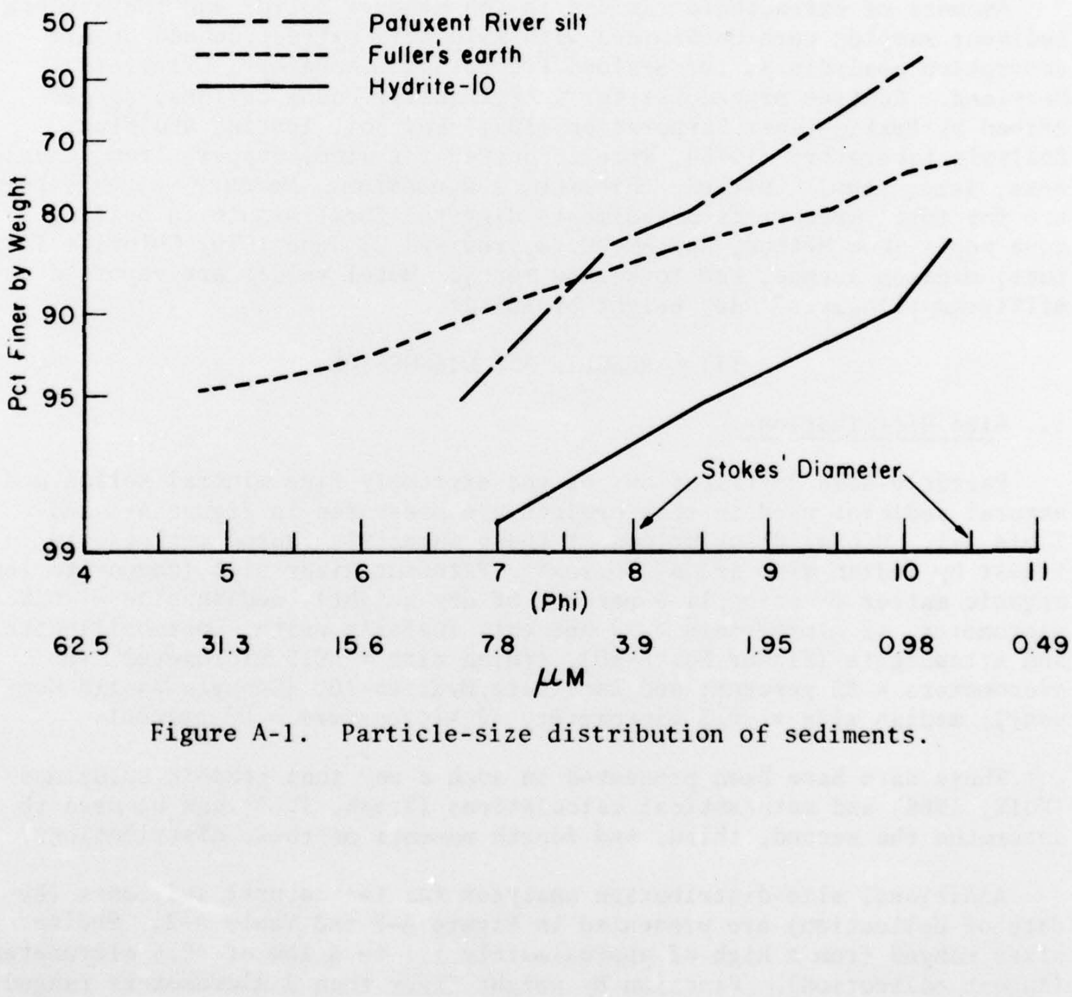

Figure A-1. Particle-size distribution of sediments.

Table A-1. Particle-size distributions of artificial sediments.[1]

Fuller's earth		Hydrite-10	
(Pct finer)	(D)	(Pct finer)	(D)
95.0	35.8	98.6	7.7
94.2	25.3	97.9	6.1
92.0	12.7	95.0	2.9
90.0	8.1	88.4	1.0
88.3	6.4	83.6	0.8
85.8	4.0		
80.0	1.6		
75.0	1.0		
73.3	0.8		

[1]Percent finer = fraction (expressed as percent) finer by weight than Stokes' diameter (D) in micrometers.

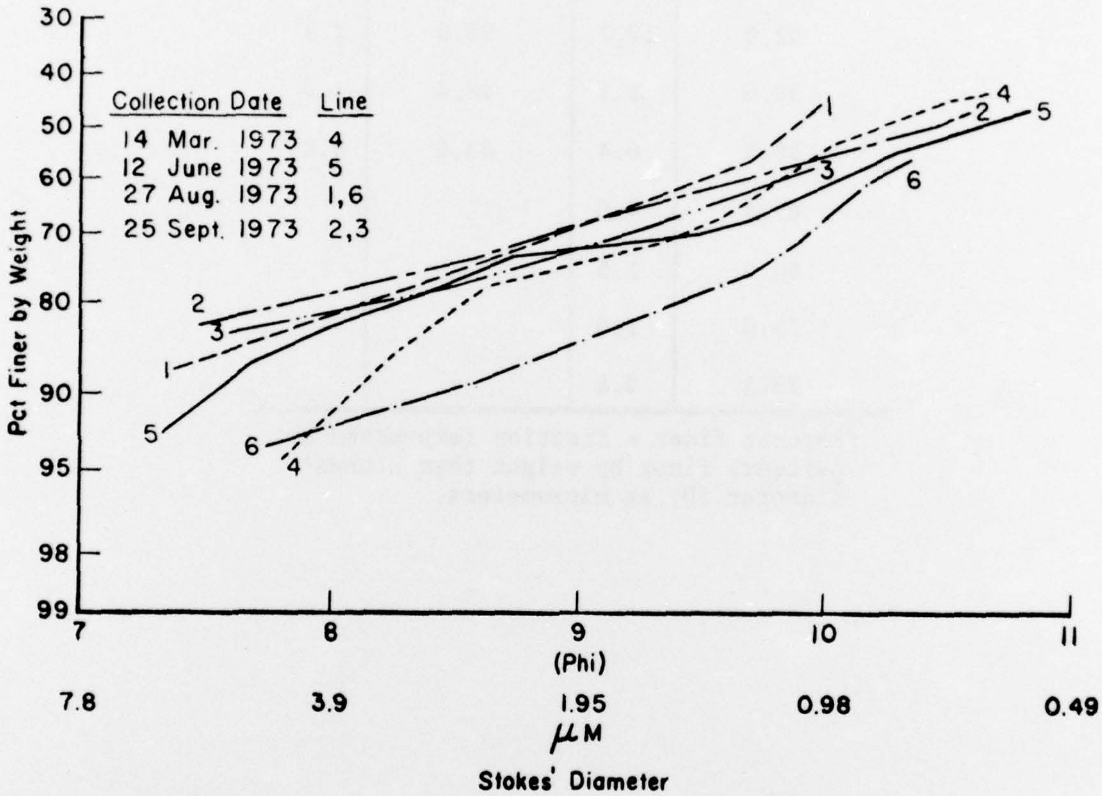

Figure A-2. Particle-size distributions of natural Patuxent River silt samples (two replicate determinations) collected by anchor dredge at Long Point.

Table A-2. Particle-size distributions of representative natural Patuxent River sediment samples collected at Long Point during 1973.[1]

14 Mar.		12 June		27 Aug.				28 Sept.			
(4) (Pct finer)	(D)	(5) (Pct finer)	(D)	(6) (Pct finer)	(D)	(1) (Pct finer)	(D)	(3) (Pct finer)	(D)	(2) (Pct finer)	(D)
95.0	4.8	92.5	6.5	93.9	4.9	87.2	6.5	83.8	4.4	80.4	4.5
86.3	3.4	84.0	4.6	89.8	2.9	74.3	2.8	77.5	2.4	75.3	3.1
80.0	2.8	79.5	3.3	77.6	1.5	58.5	1.4	74.9	2.1	71.5	2.6
77.5	2.6	74.3	2.5	75.5	1.3	54.3	1.2	73.0	2.0	68.2	2.2
70.0	1.5	69.0	1.4	73.5	1.2	45.9	1.0	63.0	1.4	51.0	0.8
65.0	1.3	67.0	1.3	67.4	1.0			60.1	1.2	47.9	0.7
62.5	1.2	64.5	1.2	61.2	0.9			55.5	1.0		
55.0	1.0	61.3	1.0	57.1	0.8						
51.3	0.9	59.3	0.9								
43.8	0.7	54.8	0.8								
		47.4	0.6								

[1]Percent finer = fraction (expressed as percent) finer by weight than Stokes' diameter (D) in micrometers. Numbers in parentheses refer to lines in Figure A-2.

Table A-3. Particle-size percentages by weight of suspended solids in the mudflow from a shell dredge (from May, 1973).

Meters from discharge	Size range (pct by weight)				
	62 to 39 μm	38 to 19 μm	18 to 10 μm	9 to 5 μm	4 to 2 μm
0	10.5	20.3	25.5	27.7	16.1
15.25	11.7	26.5	25.1	25.6	11.3
30.5	8.6	21.2	30.1	32.0	7.9
122.0	4.7	17.6	24.9	29.3	23.5
244.0	0.9	14.5	27.2	34.2	23.0

2. Organic Matter Content.

Organic matter content of natural sediment samples tended to increase throughout the summer of 1973 from a low of 8.9 percent in June to values in excess of 11 percent in August and September (Table A-4). A comparison of mean organic matter values (Table A-5) showed that these differences between earlier and later samples were significant and may indicate significant importation of organic matter, which has settled out at Long Point from marshes lining the shores of the Patuxent watershed. These organic matter values are as high as those reported by Masch and Espey (1967) for Galveston Bay.

Organic matter analyses were also conducted on the mineral solids. No significant weight loss from ashing was detectable in the fuller's earth solids. Substantial weight losses in the kaolinite (about 11 percent of dry weight) were attributed to loss of bound water (at temperatures of 500° Celsius) associated with these paper-coating and pigment-extending clays (Michael Taranto, Georgia Kaolin Company, personal communication, 1973).

3. Heavy Metals.

The mineral solids contained metal amounts that were considered biologically insignificant (Table A-6). The values reported for Patuxent silt are in the "natural" range of metal amounts found in similar estuarine salinity ranges by Huggett (Virginia Institute of Marine Science, personal communication, 1973) in the York, James, and Elizabeth Rivers which drain into the Virginia part of the Chesapeake Bay system.

Table A-4. Organic matter content of natural mud collected by anchor dredge from the Patuxent River (Long Point).[1]

Collection date (1973)	Sample no.	Organic content $\overline{X} \pm s$	S.E. $\overline{x}$
17 June	1	9.4120 ± 1.0038	0.3174
	2	10.3580 ± 1.0272	0.4594
	3	10.9400 ± 0.3270	0.1463
28 June	1	9.8740 ± 0.3808	0.1703
	2	9.4720 ± 0.4127	0.1846
	3	8.9120 ± 0.6079	0.2719
14 July	1	11.2467 ± 0.5555	0.2268
	2	10.0983 ± 0.8682	0.3545
27 Aug.	1	11.4483 ± 0.8321	0.3397
	2	11.4617 ± 0.7849	0.3205
	3	11.9700 ± 0.6712	0.2740
	4	12.6483 ± 0.4317	0.1762
18 Sept.	1	11.8567 ± 0.3038	0.1240
25 Sept.	1	11.4217 ± 0.4881	0.1993
	2	11.8750 ± 0.5131	0.2095
	3	11.2200 ± 0.4626	0.1889

[1]Samples were dried for 24 hours at 100° Celsius, ground fine with a mortar and pestle, then ashed for 3 hours at 500° Celsius. Organic matter values reported are percent loss of dry weight on ignition.

Table A-5. Comparison of means of organic matter determinations by collection date.

Sample collection dates (1973)	28 June	14 July	27 Aug.	18 Sept.	25 Sept.
17 June	N.S.[1]	N.S.	p<0.001	p<0.001	p<0.001
28 June	----	p<0.001	p<0.001	p<0.001	p<0.001
14 July		-------	p<0.001	N.S.	N.S.
27 Aug.			-------	N.S.	N.S.
18 Sept.				-------	N.S.

[1]Comparison not significant.

Table A-6. Inorganically bound cations in artificial and natural sediment.[1]

Element	Hydrite-10	Fuller's earth	Patuxent silt $\overline{X} \pm S.E.\overline{x}$ ($\overline{N}$ = 13)
Zn	0.12	0.05	36.0 ± 2.0
Cu	0.14	<0.01	4.4 ± 0.4
Fe	4.5	<0.3	2100.0 ± 94.0
Mn	<0.06	0.14	2300.0 ± 260.0
Pb	<0.5	<0.5	<10.0
Co	<0.1	<0.1	<4.0
Ni	<0.3	<0.3	<4.0
Cd	-----[2]	-----[2]	1.0
Cr	<0.3	<0.3	<3.0
Hg	<0.01	<0.01	<0.2

[1]Extraction by 0.075 N HCl-H_2SO_4 and analysis by atomic absorption spectroscopy. Values are milligram kilogram.
[2]Analysis not made.

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